NASA-CR-201922

NORTHEAST SCIENCE & TECHNOLOGY

Northeast Science & Technology
117 North Shore Blvd.
East Sandwich, MA 02537
Voice & Fax:508-833-8980

FINAL
IN-3...
...T
68805

Letter of Transmittal

Dear Sirs

Attached are the results of the NASA-funded study by Northeast Science and Technology, Inc entitled "Advanced Orion Optimized Laser System Analysis", Order No, H-27251D, dated 25 July 1996.

In this study, NST has performed a complete analysi of the solid state laser for ORION applications as per the attached SOW. The study is presented in two (2) parts. The first part analyzes the energy per pulse, allowed rep rate and the phase aberrrations produced, as well as options available to the laser engineer to provide "work-arounds" and / or mitigation techniques for these problems as required by the SOW. The second part of the study calls attention to the efficiency levels for the various device options, and bounds these efficiency levels for system analysts.

NST beleives this final report is in full compliance with all NASA requirements as delineated in the Order For Supplies or Services, attached .

J P Reilly 8/6/96
Dr. J. P. Reilly
CEO, President
Northeast Science & Technology, Inc

Distribution:

GP54 - L
CN22D
LA10 / New Technology Representative
CCO1 / Intellectual Property Counsel
COTR (Code PS02)
NASA Attn: Accessioning Dept.

Statement of Work
For Research Entitled
"Advanced ORION Laser System Analysis"

Contractor shall perform a complete analysis of the potential of the solid state laser in the very long pulse mode (100 ns pulse width, 10-30 hz rep rate) and in the very short pulse mode (100 ps pulse width 10-30 hz rep rate) concentrating on the operation of the device in the "hot-rod" mode, where no active cooling the laser operation is attempted.

Contractor's calculations shall be made of the phase aberrations which develop during the repped-pulse train, and the results shall feed into the adaptive optics analyses. The contractor shall devise solutions to work around ORION fne track issues.

A final report shall be furnished to the MSFC COTR including all calculations and analysis of estimates of bulk phase and intensity aberration distribution in the laser output beam as a function of time during the repped-pulse train for both wave forms (high-energy/long-pulse, as well as low-energy/short-pulse). Recommendations shall be made for mitigating the aberrations by laser re-design and/or changes in operating parameters of optical pump sources and/or designs.

[PPCode] NC | OMB Approval #: 2700-0042 | [Init. Ofc.]PS02

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

ORDER FOR SUPPLIES OR SERVICES

NOTE: MARK ALL PACKAGES OR PAPERS WITH ORDER AND/OR CONTRACT

PAGE 1 OF 6

ORDER NO. H-27251D

CONTRACT NO.

DO RATING* DO-C9

DATE OF ORDER JUL 25 1996

REQUISITION NO./PURCHASE AUTHORITY W-6-PP-02784 (1F)

BUREAU VOUCHER NO.

ISSUED BY: PROCUREMENT OFFICE, GP-54-L, Betty M. Canestrari
GEORGE C. MARSHALL SPACE FLIGHT CENTER
MARSHALL SPACE FLIGHT CENTER, ALABAMA 35812

BUREAU SCHEDULE NO.

SHIP TO: NASA, MSFC
Attn: PS02/Les Johnson
MSFC, AL 35812

Vendor Code: 23973
L/S Business: S
Comp/Non Comp.: NC

MAIL INVOICE (IN TRIPLICATE) TO:
FINANCIAL MANAGEMENT OFFICE, BF52
MARSHALL SPACE FLIGHT CENTER, ALABAMA 35812

TO: (Contractor name and address, including ZIP Code)

Northeast Science and Technology
117 North Shore Blvd.
East Sandwich
Cape Cod, MA 02537

DELIVERY F.O.B.: ☒ DEST. ☐ OTHER

DELIVER TO F.O.B. POINT ON OR BEFORE (Date): September 25, 1996

DISCOUNT TERMS

TYPE OF ORDER

☒ PURCHASE — Reference your quote dated July 9, 1996. Please furnish the following on the terms specified on both sides of this order and on the attached sheets, if any, including delivery as indicated.

This purchase is negotiated under authority of 10 USC 2304(g), as implemented by FAR Chapter 13.

☐ DELIVERY — This delivery order is subject to instructions contained on this side only of this form and continuation sheets, if any, and is issued on another Government agency or in accordance with and subject to the terms and conditions of the above-numbered contract.

ACCOUNTING AND APPROPRIATION DATA

806/70110 116-10-01-M900-PP-6-00S-000-2512 $ 3,000.00

UNITED STATES OF AMERICA

ORIGINAL SIGNED BY

BY JOHN C. CATHER JUL 25 1996

(Contracting/Ordering Officer) John C. Cather

SCHEDULE OF SUPPLIES OR SERVICES (Use Continuation Sheet if necessary)

ITEM NO.	DESCRIPTION	QUANTITY (No. of Units)	UNIT	UNIT PRICE	AMOUNT	QUANTITY ACCEPTED
1	ADVANCED ORION OPTIMIZED LASER SYSTEM ANALYSIS	1	1	3,000.00	$3,000.00	

REFER ALL MATTERS CONCERNING THIS ORDER TO:

GP-54-L / Betty M. Canestrari / 205-544-7178

RECEIVED AT

SHIPMENT — TYPE: ☐ FINAL ☐ PARTIAL — NO.

TOTAL $3,000.00

NOTE: See below for rejections.

DATE RECEIVED | GROSS WEIGHT | TOTAL CONTAINERS | B/L NO. | DIFFERENCES

RECEIVED BY | CARRIER | VERIFIED CORRECT | FOR (Amount) | INITIALS

QUANTITIES IN "QUANTITY ACCEPTED" COLUMN HAVE BEEN: ☐ INSPECTED ☐ ACCEPTED ☐ RECEIVED BY ME, AND CONFORM TO CONTRACT (Items listed below have been rejected for reasons shown)

BY ______________________ ______________
(Authorized U.S. Govt. Representative) (Date)

I CERTIFY THAT THIS ACCOUNT IS CORRECT AND PROPER FOR PAYMENT

BY ______________________
(Signature and title of Certifying Officer)

REJECTIONS

ITEM NO.	DESCRIPTION	UNIT	QUANTITY	REASON

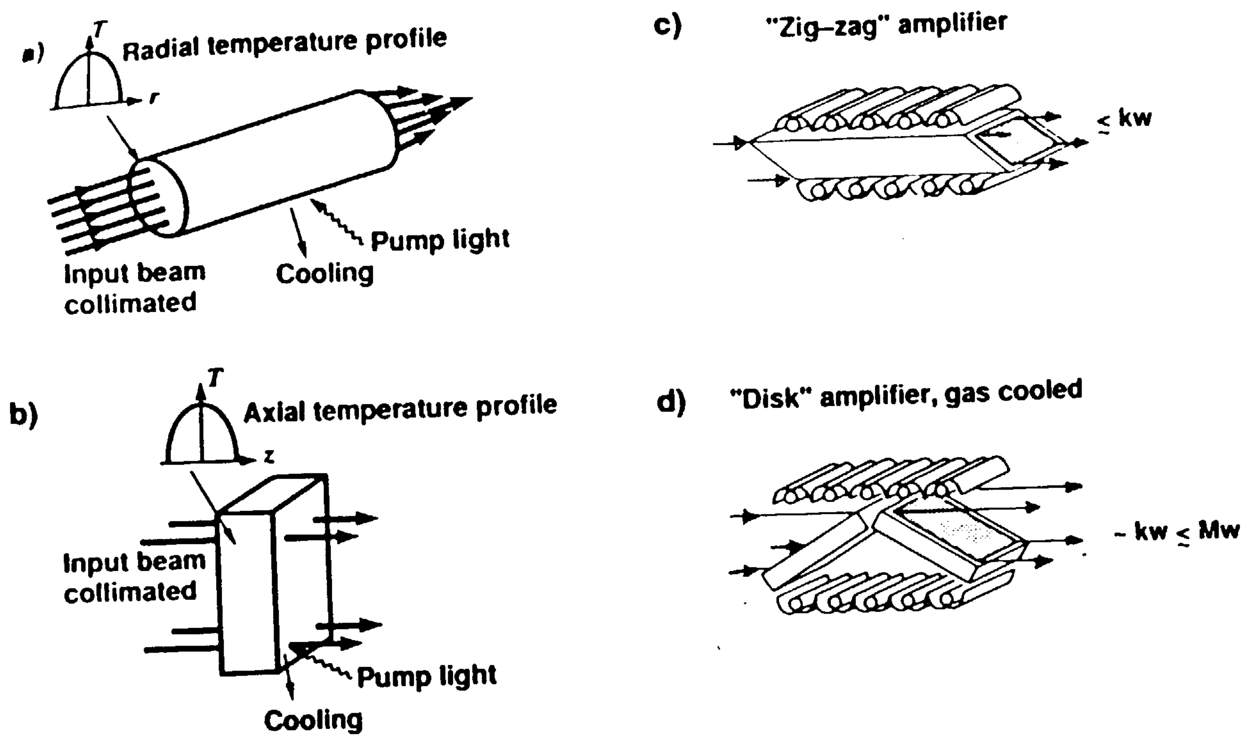
*Certified for National Defense under DMS Reg. 1

The DMS rating shown must be placed on all purchases by your firm in support of this order.

MSFC-FORM 3988 (REV. SEPTEMBER 1985)

Repped-Pulse Solid State Analysis

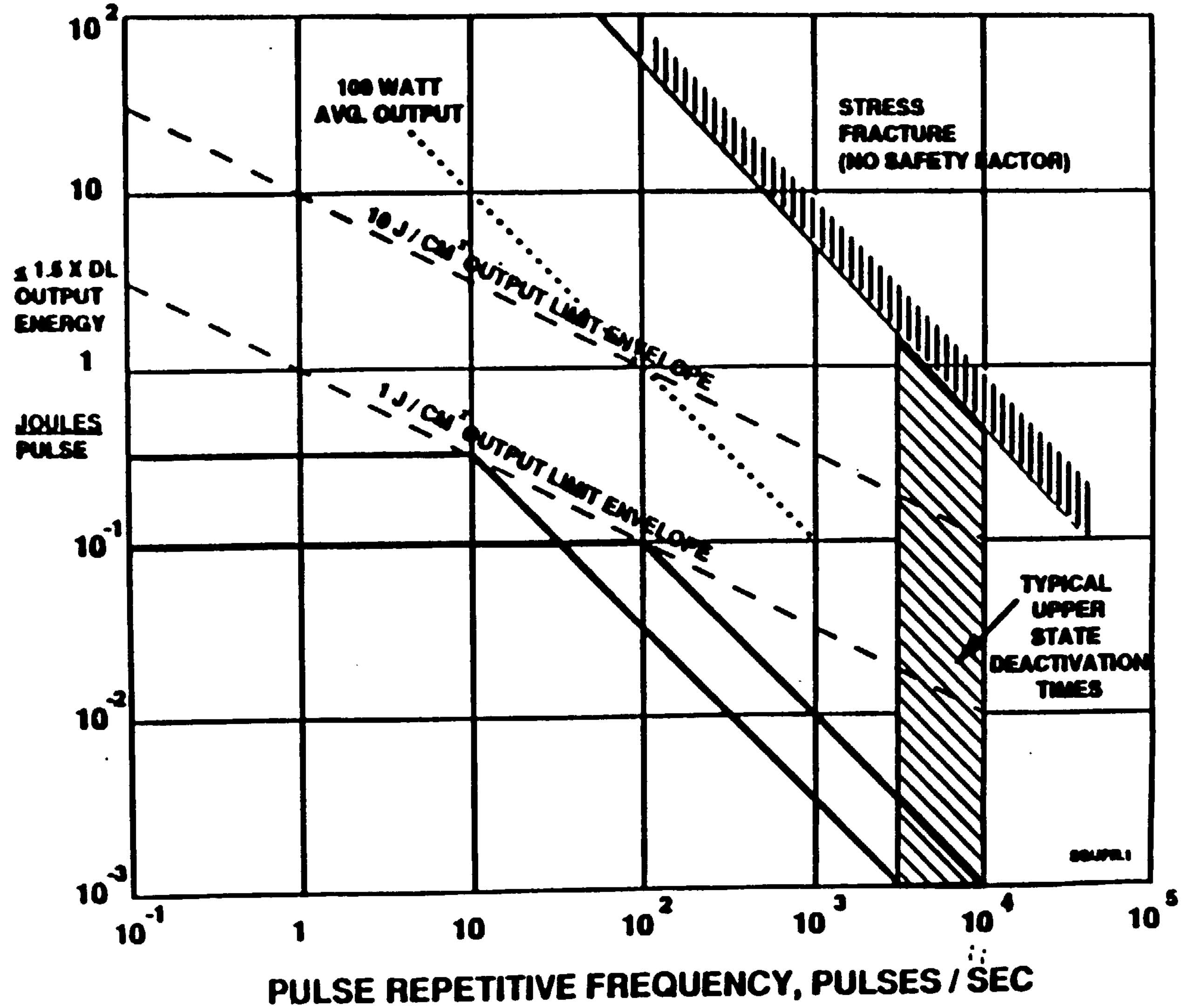
Repped Solid State Geometries



Rep-rate issues for Solid State Lasers

All rep-rate damage appears to stem from Thermal Deposition and Inadequate Heat Removal

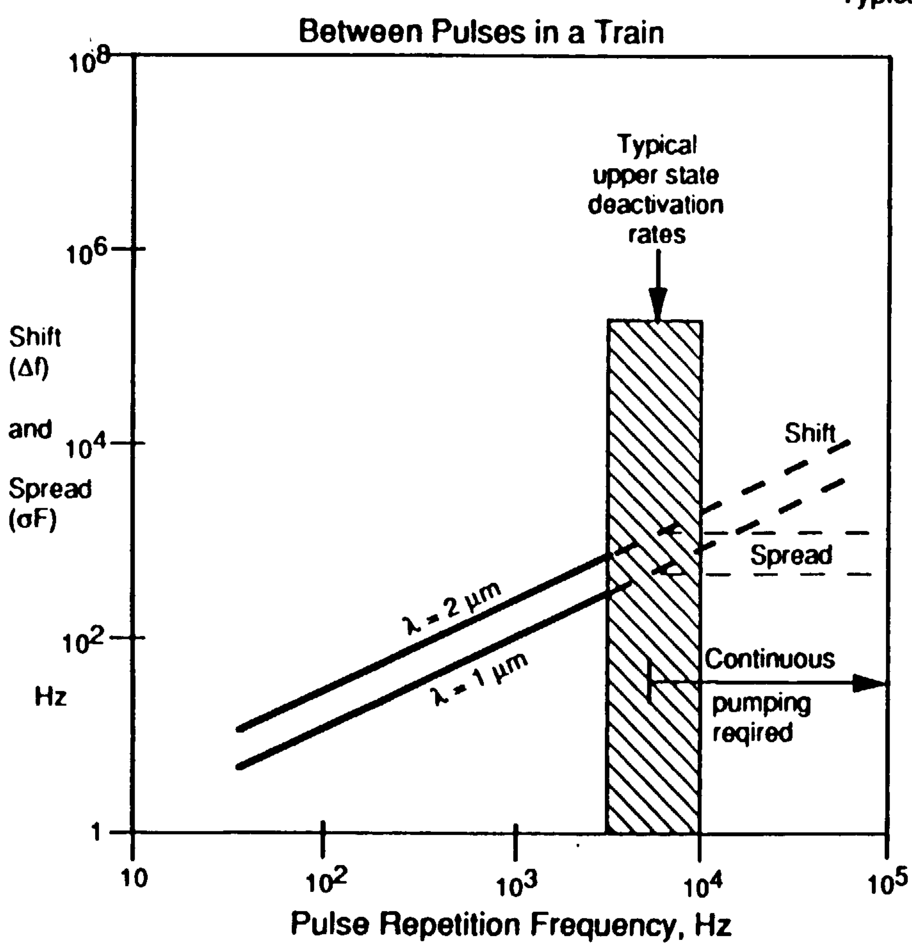
Fracture	thermal profile buildup induces-- tension in outer (free) edges -- compression in center (free) region
Photoelastic	stress-induced changes in refractive index at laser wavelength
Thermal Lensing	symmetrical thermal change in refractive index causes beam divergence
Stress Bi-Refringence	stress-induced changes in refractive index over range of wavelengths
Beam Steering	asymmetric thermal changes in refractive index causes beam steering
Differential Expansion	between gain mat'l and transmission-face coatings as well as edge-band coatings
Inclusions / Interfaces	surface and bulk sites show --higher linear absorption than bulk deposition, and/or --higher electric field concentrations with local heating higher than bulk deposition

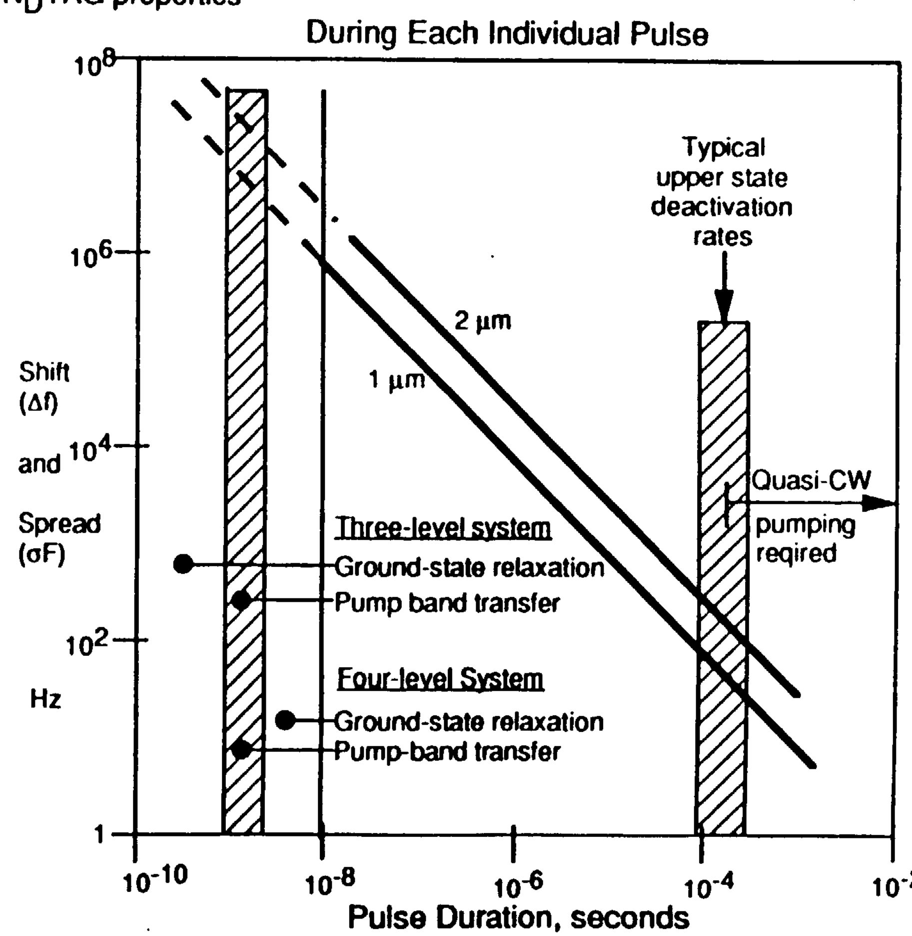


Cylindrical Geometry Solid State Technology Does Not Scale to High Average Power

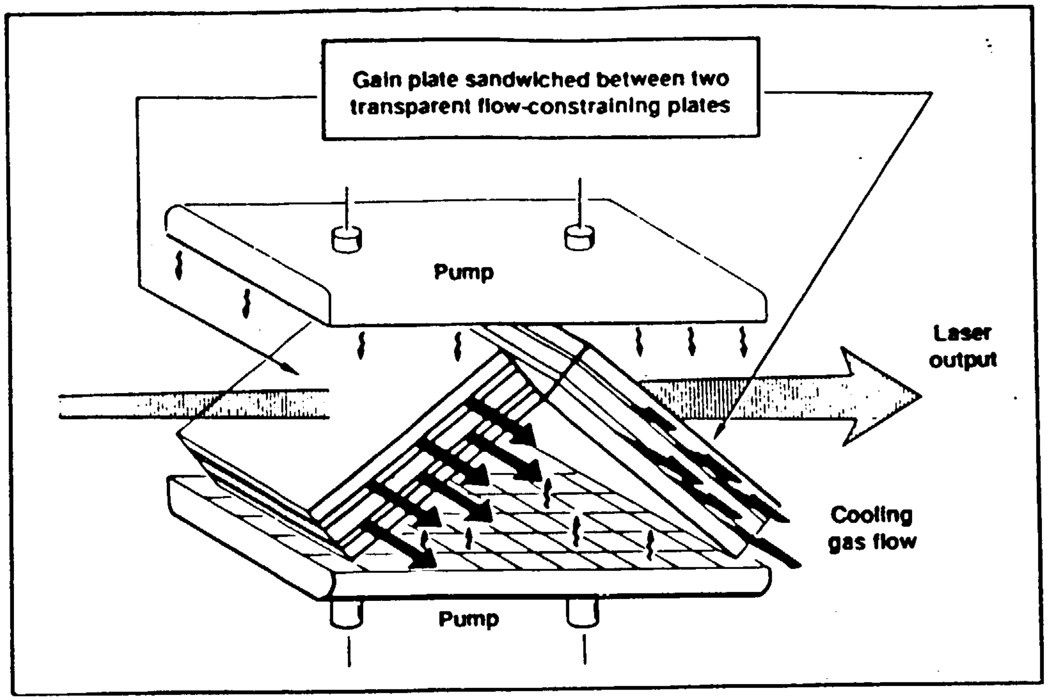
PULSE REP-RATE AND PULSE DURATION EFFECTS ON SOLID-STATE AMPLIFIER OUTPUT FREQUENCY SHIFT AND FREQUENCY SPREAD

<u>Assumptions:</u> 75% quantum efficiency
60% extraction efficiency at core
No extraction at edge
Typical N_DYAG properties





Cooling the Slabs is Key to Slab Array Design



Key Scaling Issues in Cooling of Slab Laser Gemotries

1- Allowable Thermal Limits on Laser Slabs Materials and Geometry

2- Allowable Thermal Limits on Transmissive Optics which contact Cooling Fluid

3- Flow Characteristics of cooling fluid (gas, liquid) and how it transfers heat from the hot laser slabs

4- Power Requirement to perform this cooling and how it affects overall efficiency

5- Beam Losses and distortions due to passage through turbulent flow in cooling passages

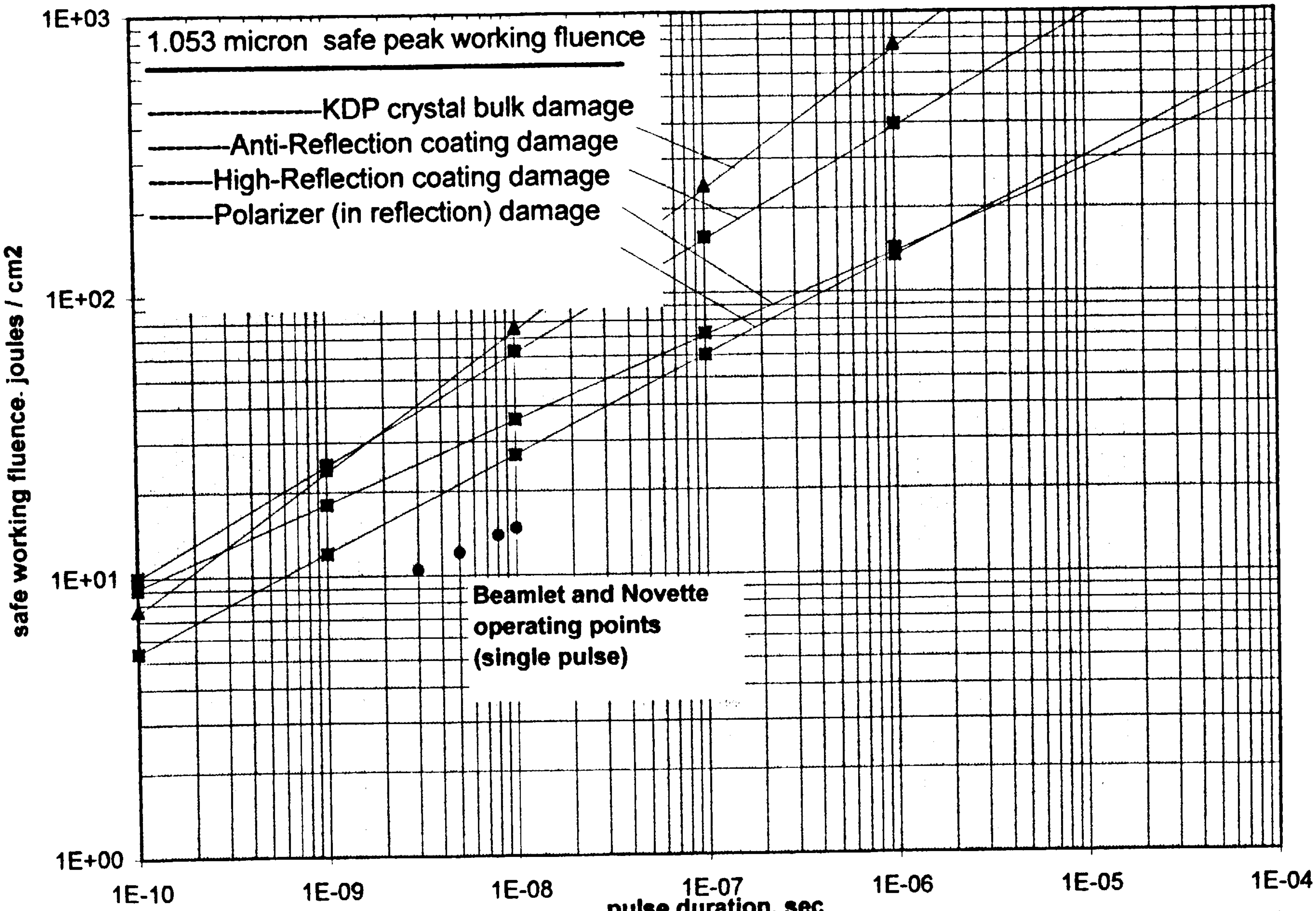
6- Beam Losses and distortions due to passage through turbulent flow in Drift Spaces

Scaling of Repped Solid-State Lasers

Average Power Output = J_{lim} (joule/cm^2 per pulse) x A_{beam} (cm^2) x PRF (pulses / sec)

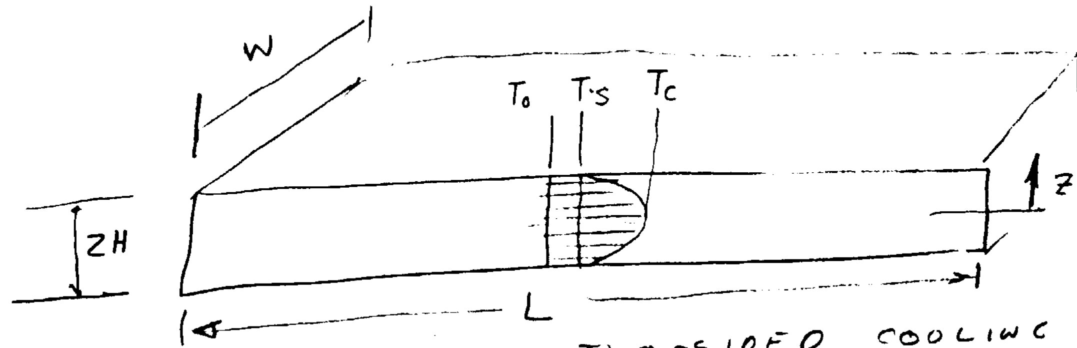
J_{lim}	A_{beam}	PRF
Limited by : - Single Pulse Damage - Distortion	Limited by : -Manufacturing Processes -Avg Power Cooling	Limited by : -Thermal Recovery between pulses - Avg Power Cooling

Limiting Single Pulse Fluence in ND:Glass Beamlet Train



LLNL Beamlet and Novette Lasers have Demonstrated 10-20 j/cm^2 Optics

FORCES ON A HEATED THIN SLAB WITH SURFACE COOLING



- UNIFORM HEAT DEPOSITION AND TWO-SIDED COOLING

$$\left(\frac{T_c - T(z)}{T_c - T_s}\right) = \left(\frac{z}{H}\right)^2$$

- CENTER REGION EXPANDS MORE THAN SURFACES, PULLING THEM ALONG, INDUCES TENSILE STRESS IN EACH EXTERIOR SURFACE & COMPRESSION AT CENTER. MOMENT CAUSES

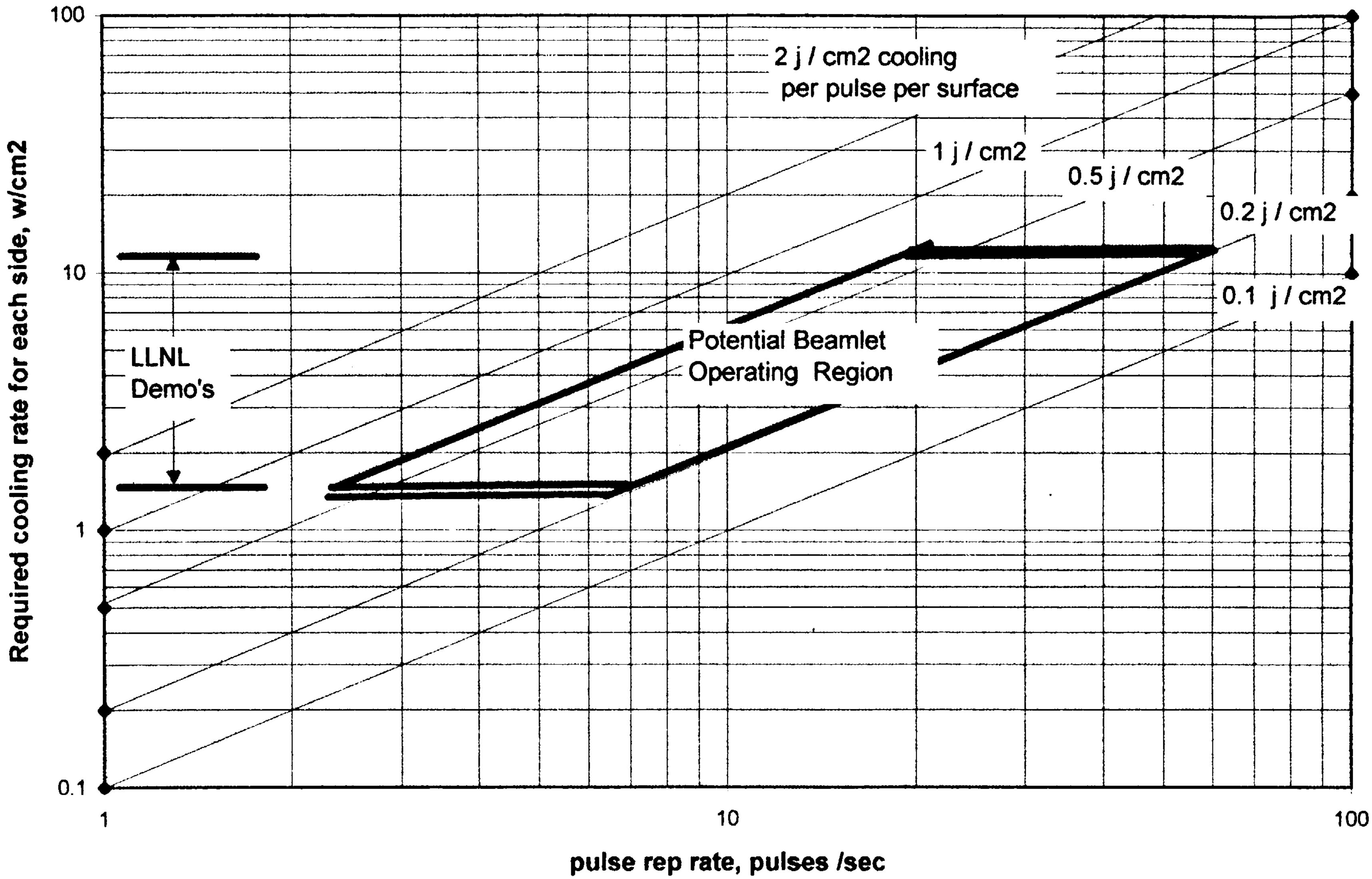
$$\sigma = \alpha E\left[-T(z) + \frac{1}{2H}\int_{-H}^{+H} T(z)\,dz + \frac{3}{2}\left(\frac{z}{H^3}\right)\int_{-H}^{+H} T(z)\,z\,dz\right] = \alpha E\left(T_c - T_s\right)\left[\frac{1}{3} - \left(\frac{z}{H}\right)^2\right]$$

- IF COMPRESSIVE END-CONSTRAINT IS IMPOSED, A UNIFORM COMPRESSIVE STRESS IS SUPERPOSED

$$\sigma = \frac{\alpha E}{(2H)}\int_{-H}^{+H} \Delta T\,dz = \frac{\alpha E}{2H}\left(T_c - T_s\right) H \frac{1}{3} = +\frac{1}{6}\alpha E\left(T_c - T_s\right)$$

NET STRESS	AT SURFACE	$\sigma / \alpha E (T_c - T_s)$	$= -2/3$ TO $-1/2$	≈ -0.60
	~~AT CENTER~~	$\sigma / \cancel{\alpha E (T_c - T_s)}$	$= \cancel{+1/3}$ TO $+1/2$	$\approx +0.40$

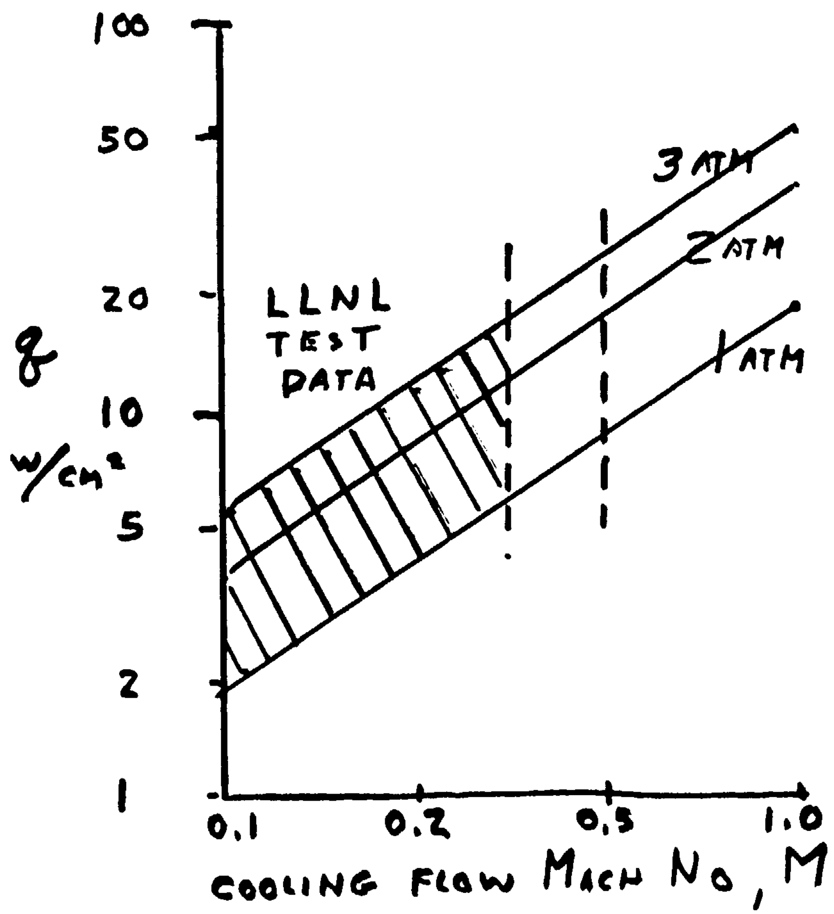
Required and Demonstrated Heat Transfer Rates



LLNL Demonstrated Cooling Rates and Energy Deposition Indicates 10 - 20 hz Appears Feasible

NST Northeast Science & Technology

Gas-Flow Cooling can Support Continuous Operation



$$q = S_T \, \rho \, U \, C_p \left(T_{WALL} - T_{GAS}\right)$$

$$= S_T \, P \, M \, \frac{C_p}{R} \, a \left(\frac{T_{WALL} - T_{GAS}}{T_{GAS}}\right)$$

HELIUM: $c_p/R = 2.5$

$a = 8.7 \times 10^{4}$ cm/s AT 300 °K

$S_T = 0.005$ (TURB)

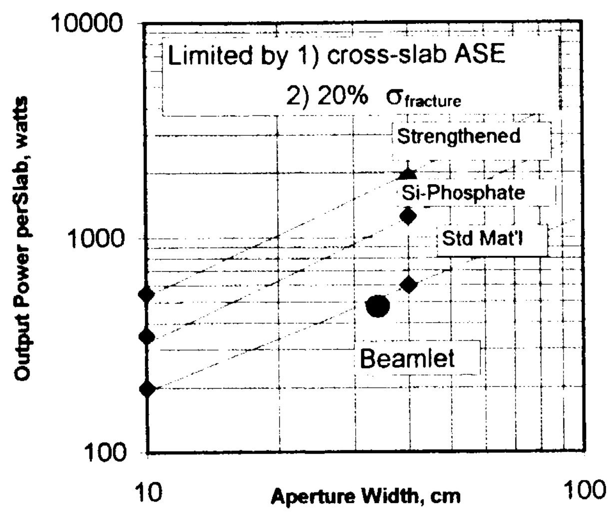
$T_{GAS} = 300$ °K

$T_{WALL} = 350$ °K

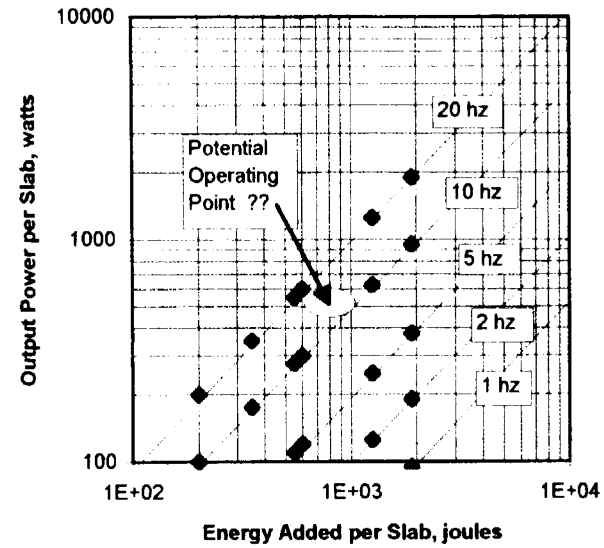
HELIUM COOLING FLOW ON EACH SLAB FACE

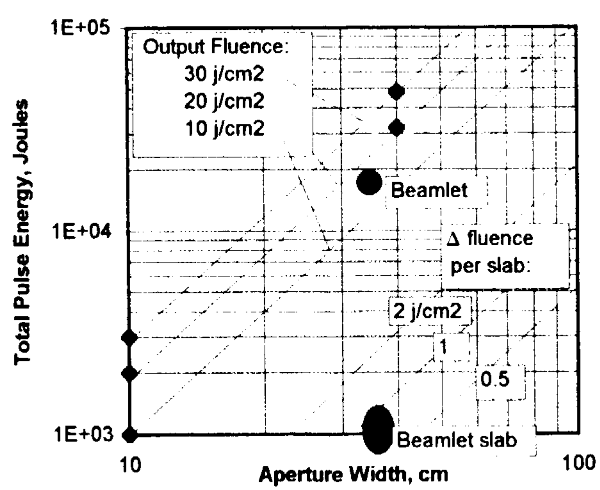
- HEAT TRANSFER ALLOWS CONTINUOUS OP'N
- PRESSURES TO 3 ATM ALLOW LOW SCATTERING LOSSES BELOW M = 0.5
- PUMPING POWER LOSSES NEGLIGABLE BELOW M = 0.3

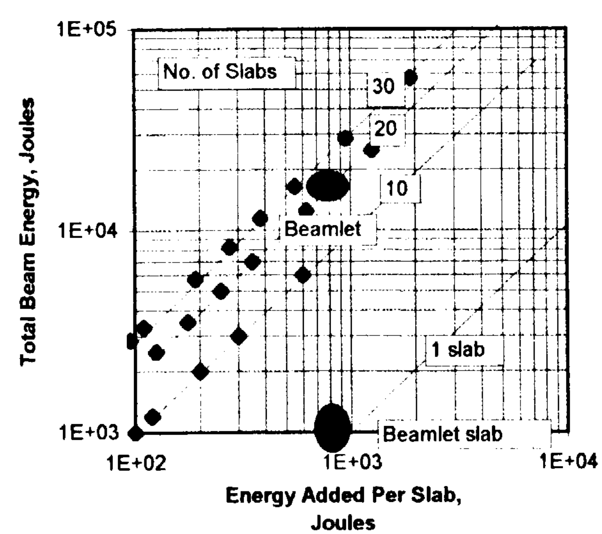
Scaling of Rep-Pulse Solid-State Slab Lasers



Ref: J.A.P. Vol 69 No 3, 1 Feb 1991







(b) Prototype Beamlet

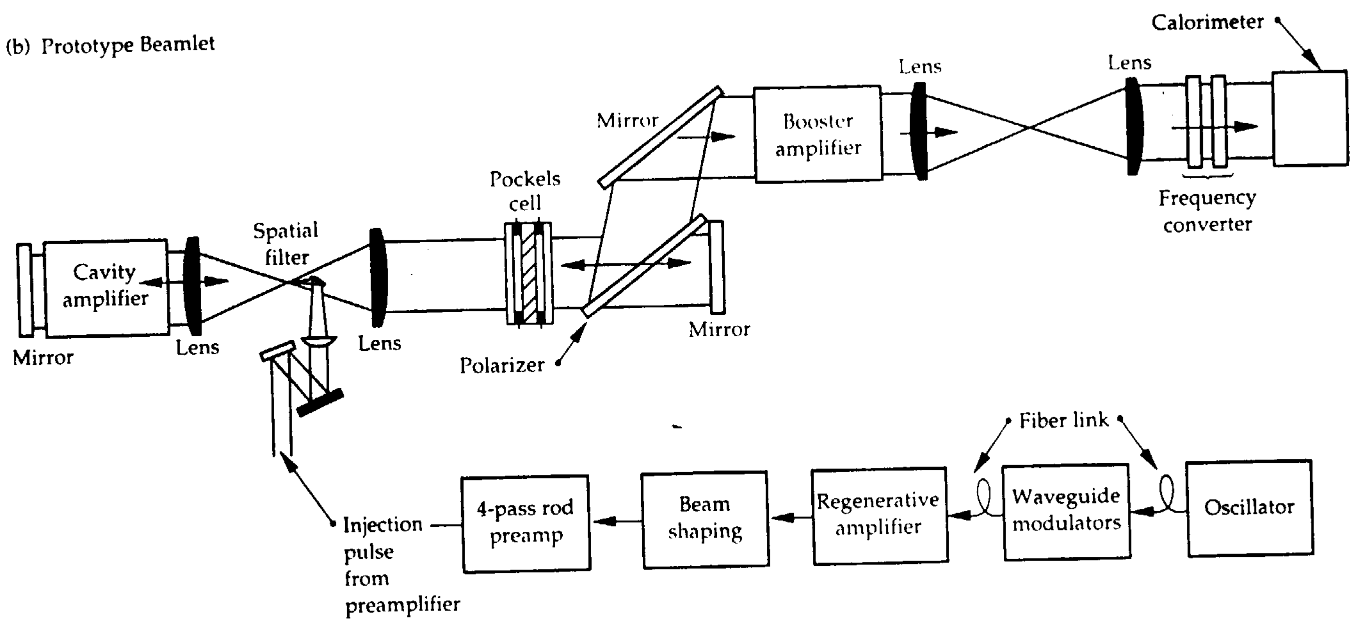


FIGURE 3. (a) Schematic drawing of the multipass NIF laser design. (b) Prototype Beamlet design. (40-00-0394-0789pb02)

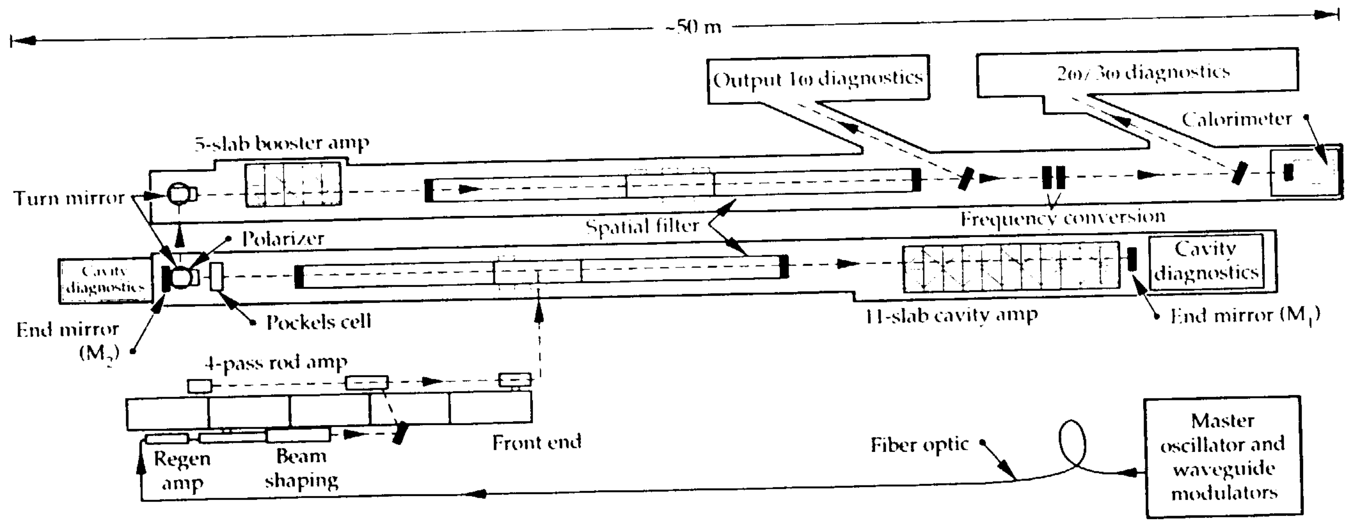
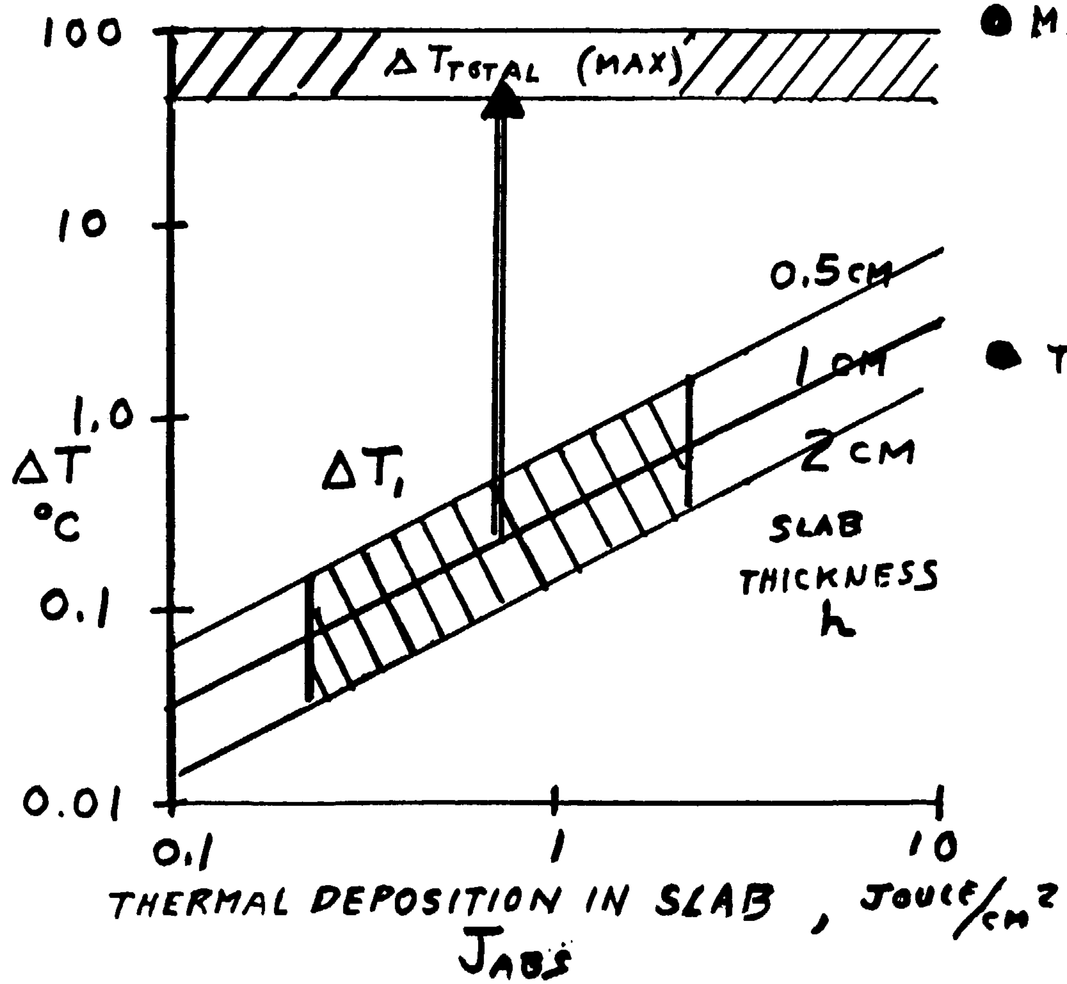


FIGURE 5. Plan view of Beamlet as configured for the tests described in this article. (02-30-1091-3760Epb01)

Uncooled - Burst Operation
- A possible Near-Term Demo

"Hot Rod" concept for near-term demo of solid-state laser
- ref: Battelle Columbus proposal / small-scale demo
- ref: LLNL design / proposal to P.L.'s ABL Program Office



- MAX TOTAL ΔT FOR 10% GAIN LOSS

  3.3% Nd_2O_3 LHG-5 GLASS

  $T_{MAX} = 350°K$ $(g_0 = 0.01/cm)$

  $T_{MAX} = 400°K$ $(g_0 = 0.05/cm)$

- TEMPERATURRISE PER PULSE

  $J_{ABS} = \rho C \Delta T_1 h$

100 - 1000 PULSE BURST WITHOUT COOLING

ALLOWS POSSIBLE NEAR-TERM DEMO

Conclusions from Repped-Pulse Laser Source Study

1- The closest tool at our disposal for the pusher laser application is a repped-pulse version of the Beamlet or Novette devices at LLNL

- the **demonstrated single-pulse energy** is high enough to serve as a **pusher**, satisfy plasma ignition, "optimum" plasma impulse coupling and simple surface-vaporization-reaction impulse production, given our canonical 40 cm spot at range.

- the **demonstrated single-pulse energy** is high enough to serve as an **illuminator,** acting as a handover tool from a typical 100-200 meter dia microwave radar acquisition region so as to refine the target position sufficiently for the pusher function to be accomplished with the smaller (40 cm dia) spot at range.

- the **required pulse repetition rates** for the **pusher** function (10 - 50 hz range) appears to be achievable with the current Beamlet slab materials, the current slab heat loading and flashlamp pumping, and the current Helium-flow cooling technology to achieve safe operation of the laser and good (not perfect) beam quality---the adaptive optic may have to compensate for some of the aberrations. The flashlamps, power supplies and beam aberrations need further examination.

- the **required pulse repetition rates** for the **illuminator** function (10 - 100 hz range) appears also to be consistent with these demonstration of cooling technologies, heat loading and beam quality levels. Aberrations are less important for the illuminator function (because of the large spot) than for the smaller-spot pusher function.

The only realistic option for Orion in the near term is with LLNL's technology and personnel. Even so, funding would have to be provided from somewhere, perhaps as a "joint venture" with DOE' s National Ignition Faciltiy effort.

AN ISSUE FOR THE COST ANALYSES AND TRADE STUDY :

EFFICIENCY OF SOLID STATE LASERS CAN BE VERY LOW

System Efficiency Drives Power Supply Cost

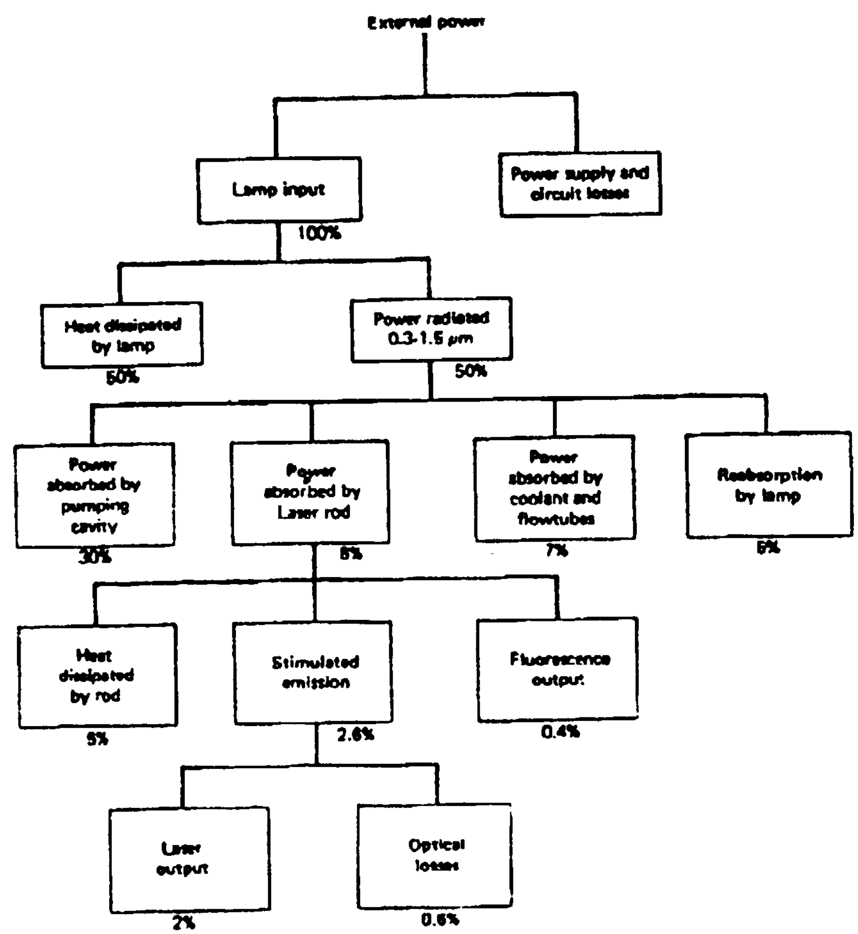
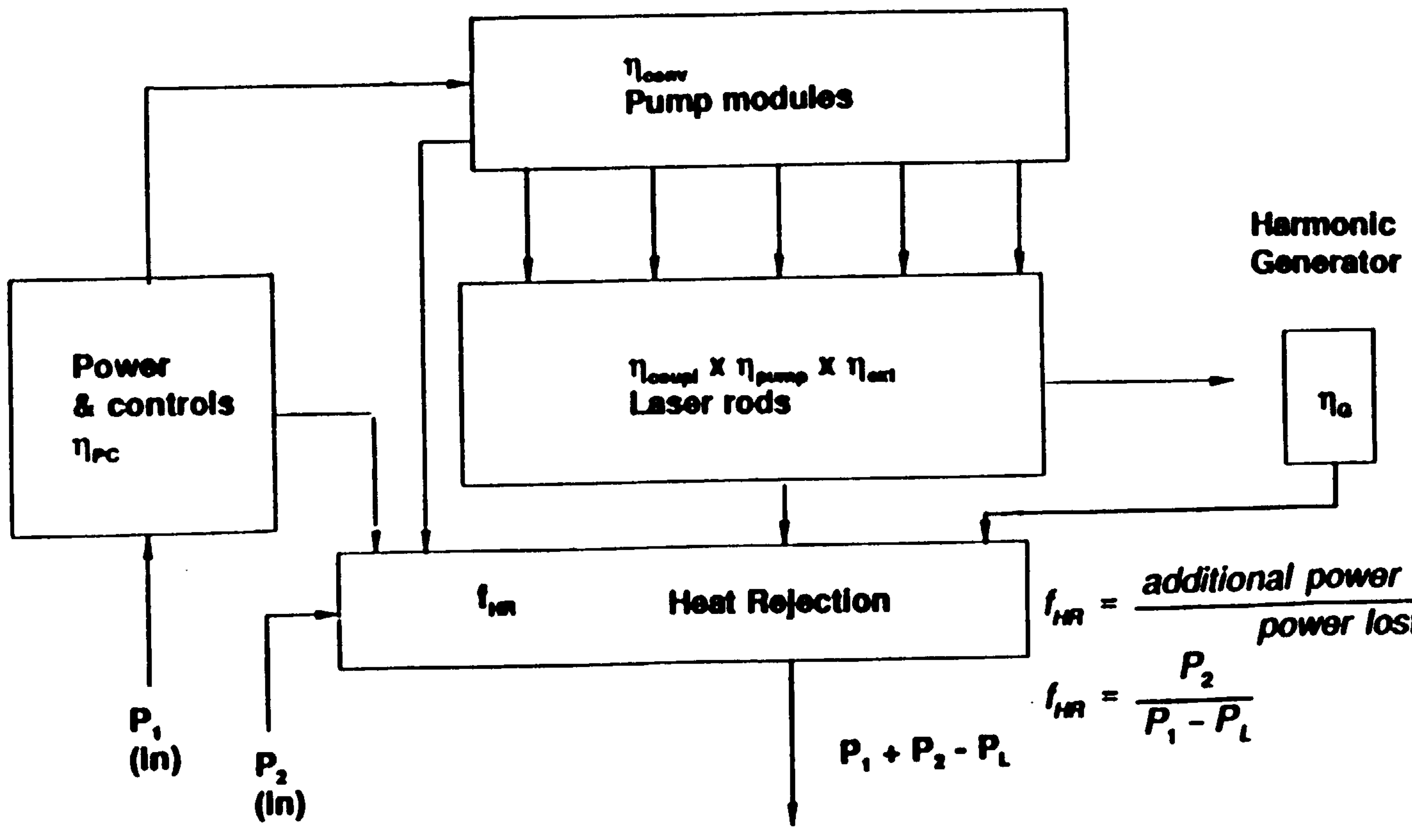


Fig. 6.75. Energy balance in an optically pumped solid-state laser system. (The percentages are fractions of electrical energy supplied to the lamp)

SOLID STATE SYSTEM EFFICIENCY



$$f_{HR} = \frac{\textit{additional power required into heat exchange}}{\textit{power lost from rest of system}}$$

$$f_{HR} = \frac{P_2}{P_1 - P_L}$$

$$\eta_{tot} = \frac{\textit{laser power out}}{\textit{total power in}} = \frac{P_L}{P_1 + P_2} = \frac{P_1 \times \eta_{PC}\,\eta_{conv}\,\eta_{coupl}\,\eta_{pump}\,\eta_{ext}\,\eta_G}{P_1 + P_1(1 - \eta_{PC}\,\eta_{conv}\,\eta_{coupl}\,\eta_{pump}\,\eta_{ext}\,\eta_G)(1 + f_{HR})}$$

DIODE-PUMPED SOLID-STATE LASER SYSTEM EFFICIENCY AND TYPICAL VALUES

$$\eta_{total} = \frac{\eta_{PC}\ \eta_{conv}\ \eta_{coupl}\ \eta_{ext}\ \eta_{G}}{1 + (1 - \eta_{PC}\ \eta_{conv}\ \eta_{coupl}\ \eta_{pump}\ \eta_{ext}\ \eta_{G})\ (1 + f_{HR})}$$

η_{total}: System range
1.1%-14.1%

η_{PC}: Power conditioning and controls
80%-90%

η_{conv}: Conversion to diode output in pump band
30%-50%

η_{coupl}: Optical coupling
70%-90%

η_{pump}: Absorbed pump x quantum effic. x Stokes shift
(70%-90%) x 90% x 76%

η_{ext}: Extraction
70%-90%

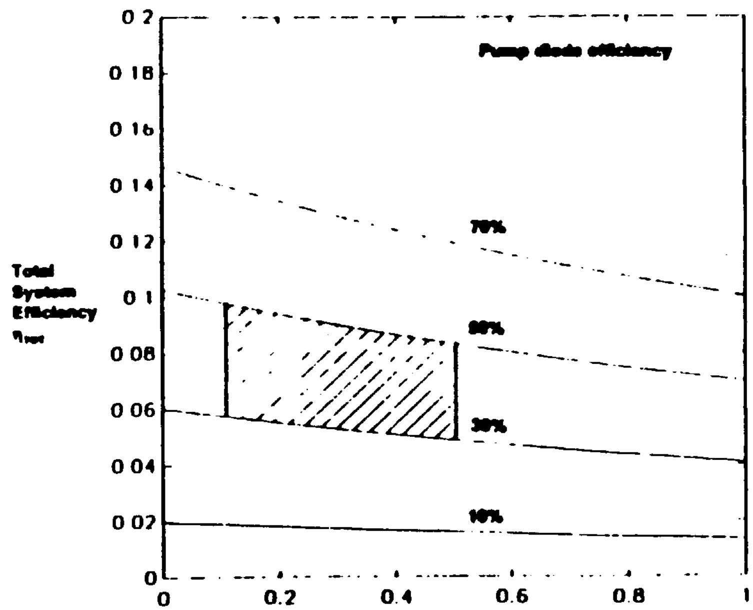
η_{G}: Harmonic generation
40%-70%

f_{HR}: Heat rejection
50%-90% efficiency
($0.1 \le f_{HR} < 0.5$)

Diode conversion and heat rejection efficiency show biggest payoff potential for system efficiency

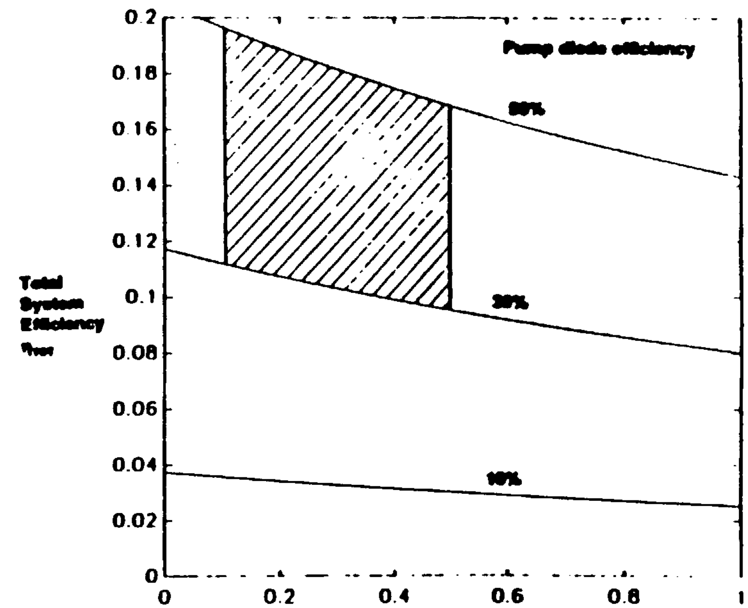
DIODE-PUMPED SOLID STATE LASER SYSTEM EFFICIENCY RANGES

Lower bounds on all other component efficiencies



f_{HR}
Fractional additional power required to remove heat from system

Upper bounds on all other component efficiencies



f_{HR}
Fractional additional power required to remove heat from system

With careful engineering, solid state systems can have 7%-15% system efficiencies